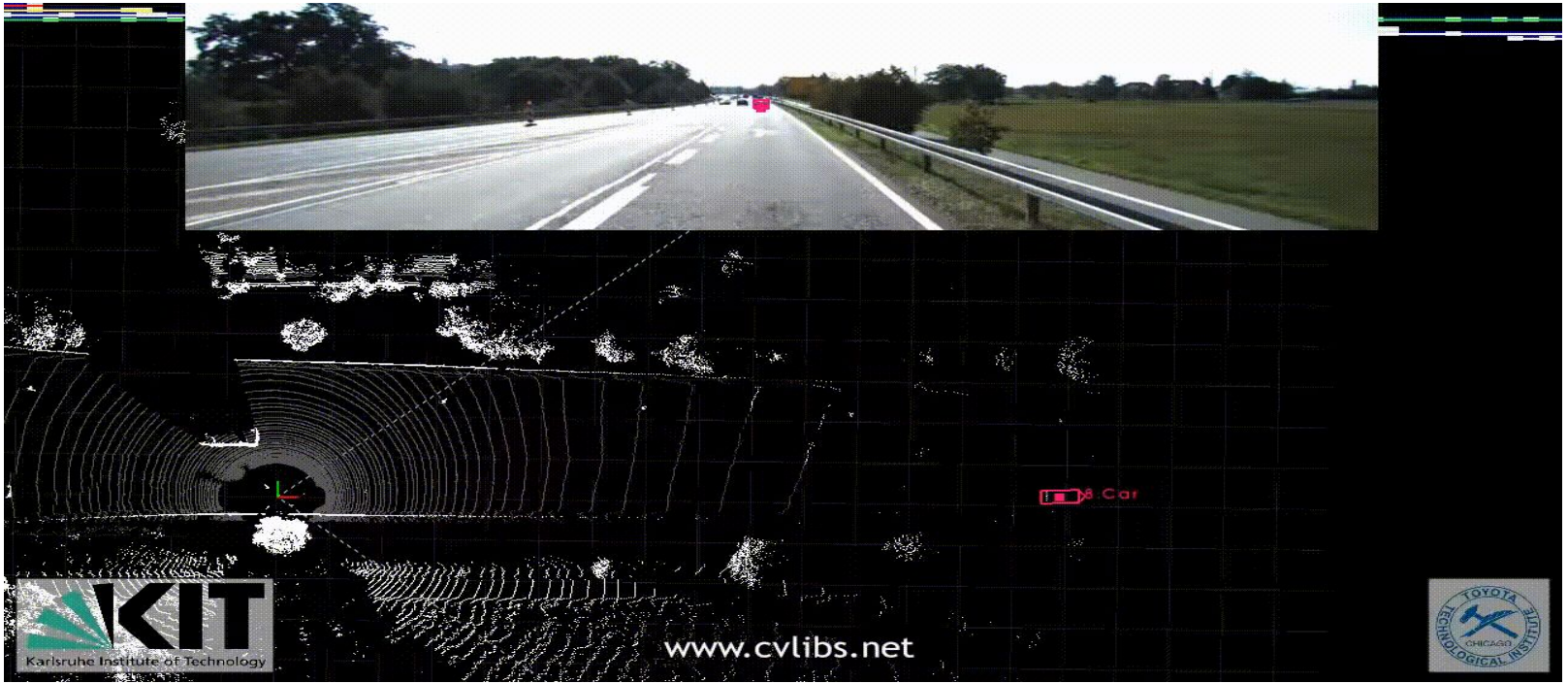
Robust 3D Object Detection using Probabilistic Point Clouds from Single Photon LiDARs

ICCV 2025

https://bhavyagoyal.github.io/ppc

3D Inference with LiDAR Point Clouds

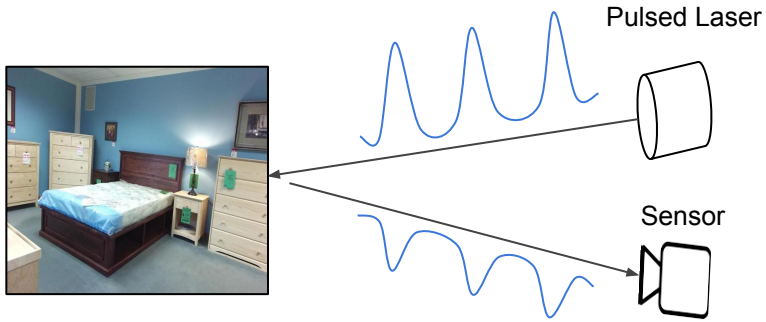


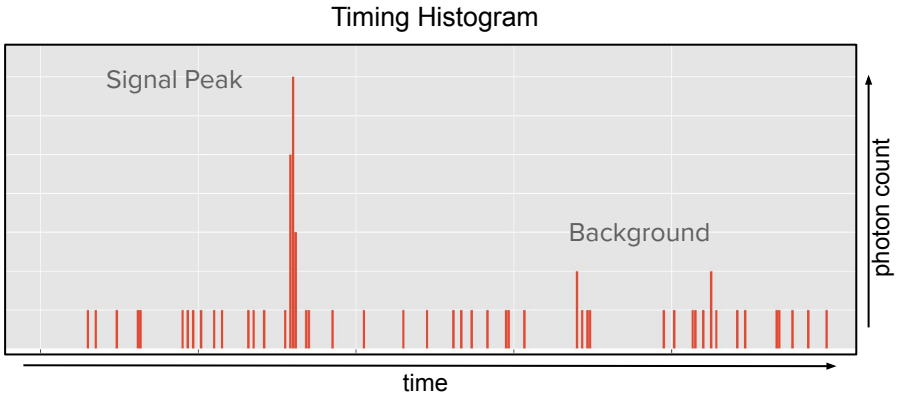
Point Clouds are often Sparse and Noisy

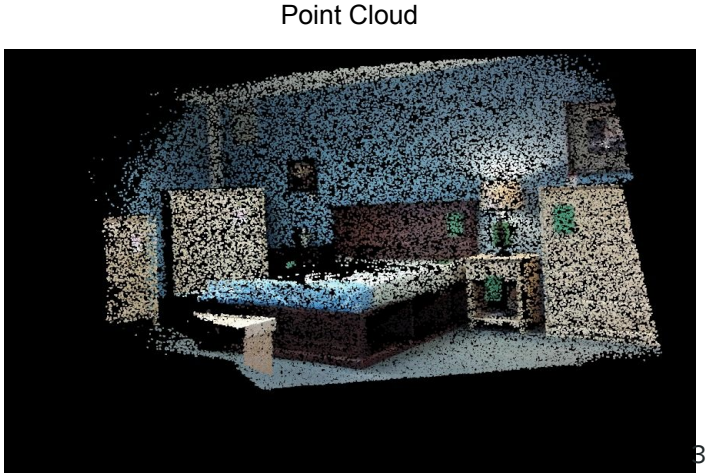
Smaller and Farther objects are challenging

Source: KITTI Vision Benchmark Suite

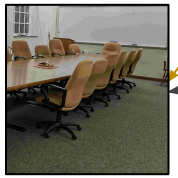
3D Sensing with a LiDAR

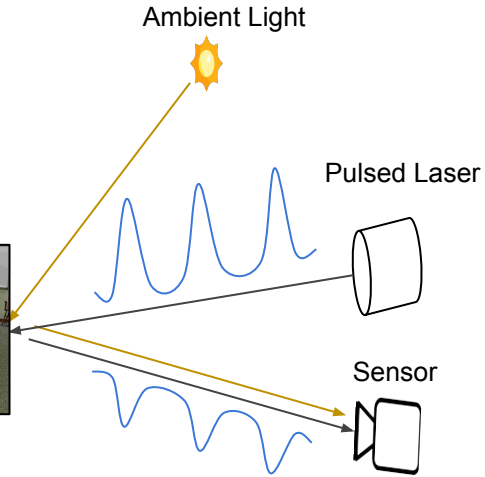


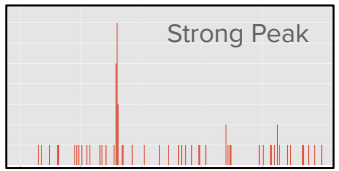




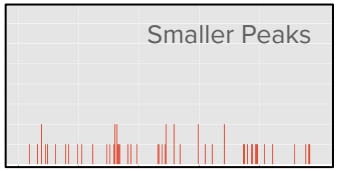
3D Inference Pipeline with LiDAR



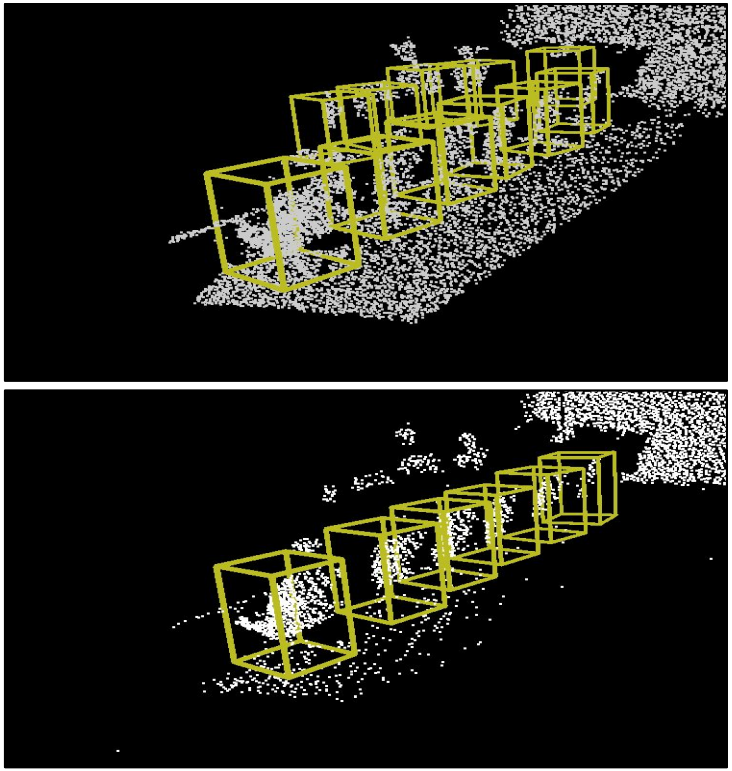




Ideal (High SBR)



Challenging (Low SBR)



Challenging Low SBR in 3D Sensing

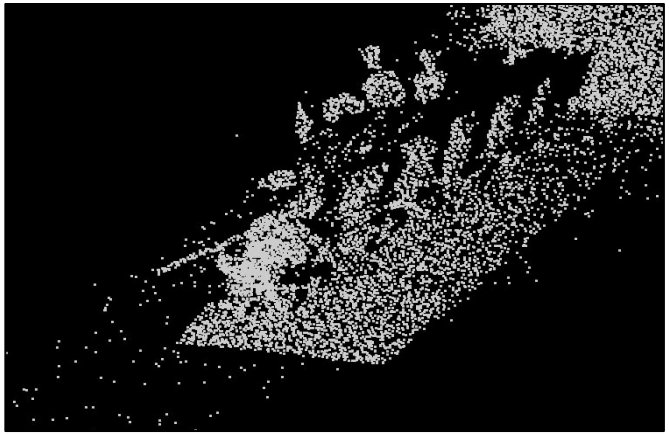
- Power constraints
- Lightweight sensors
- Low scene albedo
- Long distance
- Strong ambient light
- And more

Resource Constrained Devices

3D Inference in Low SBR

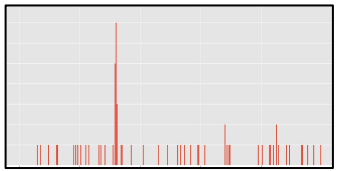
- Noisy and Sparse point clouds in Low SBR
  - Misses farther objects: cars

Augmenting Point Cloud with Confidence

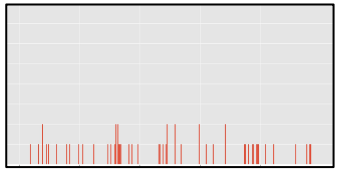


Point Cloud
[x, y, z]

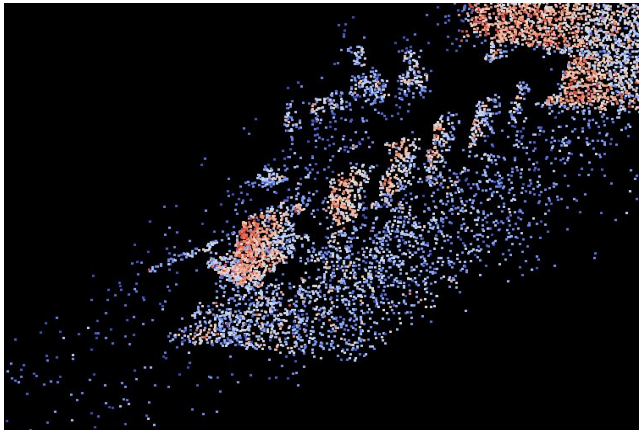
Timing Histogram



High SBR



Low SBR

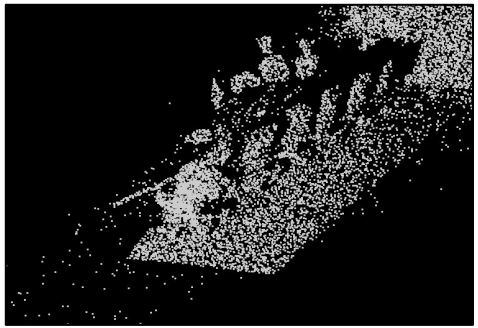


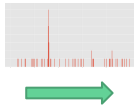
Probabilistic Point Cloud (PPC)
[x, y, z, p]

$$Pr(p^{ij}) = \frac{h_{i,j}[m]}{\sum_{n=1}^{N} h_{i,j}[n]}, \qquad \text{where} \quad m = \arg\max_{n} \; h_{i,j}[n]$$

Inference with Probabilistic Point Cloud (PPC)

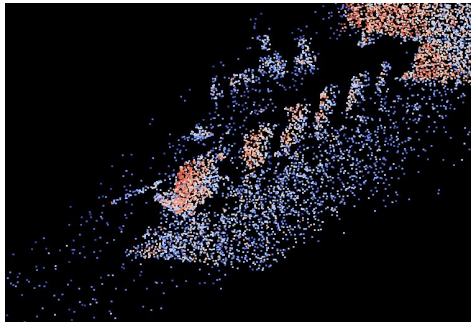
Point Cloud



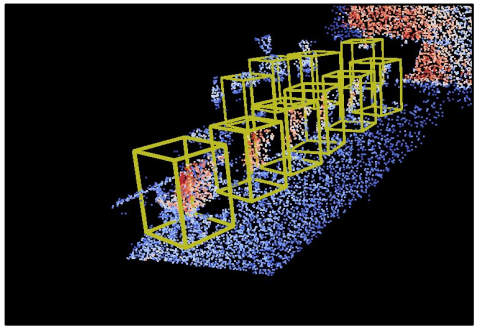


Probability Attribute

Probabilistic Point Cloud (PPC)



Robust Inference using PPC



- Probabilistic Point Cloud (PPC) from LiDARs
  - Robust Inference using PPC

3D Inference with PPC

- Neighbor Probability Density Filtering (NPD)
- Farthest Probable Point Sampling (FPPS)
- Probability Aware 3D inference networks

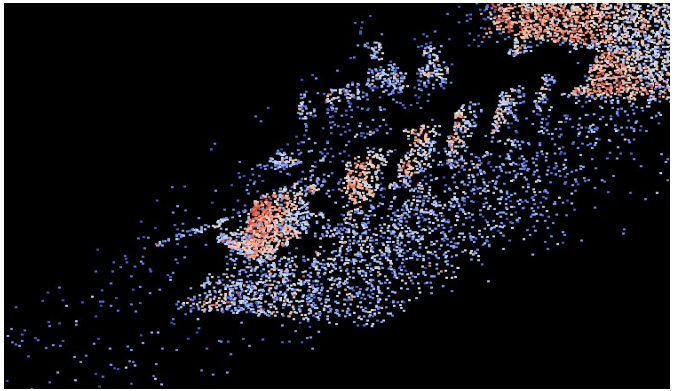
3D Inference with PPC

- Neighbor Probability Density Filtering (NPD)
- Farthest Probable Point Sampling (FPPS)
- Probability Aware 3D inference networks

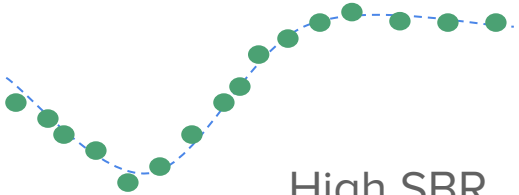
Noise in Low SBR

- Spurious points
  - Arbitrarily far from a surface/object

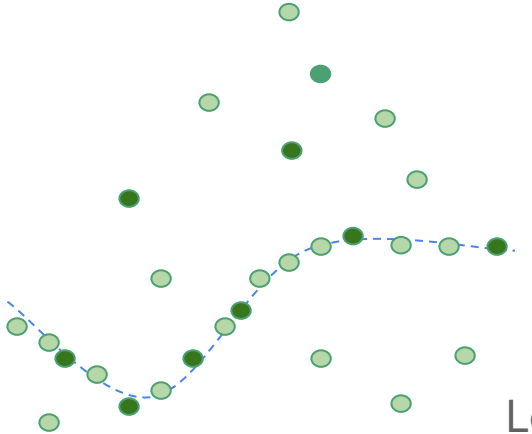
- High Spatial Density of points on surface



Probabilistic Point Cloud (PPC)



High SBR



Low SBR

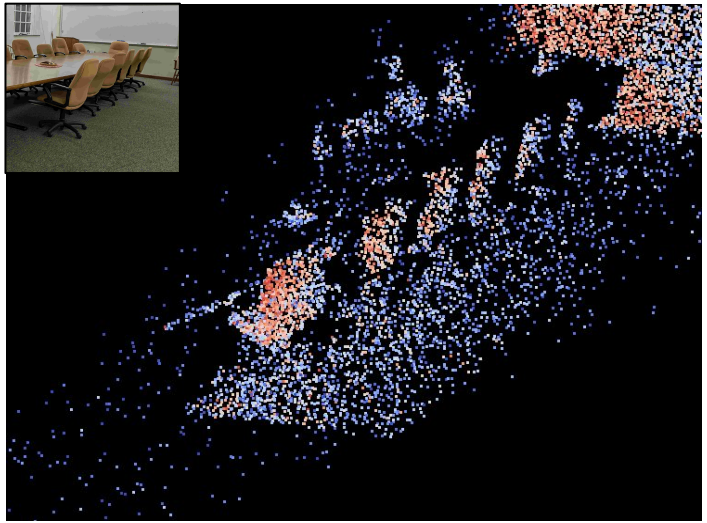
Noise Removal

Neighbor Probability Density (NPD) Filtering

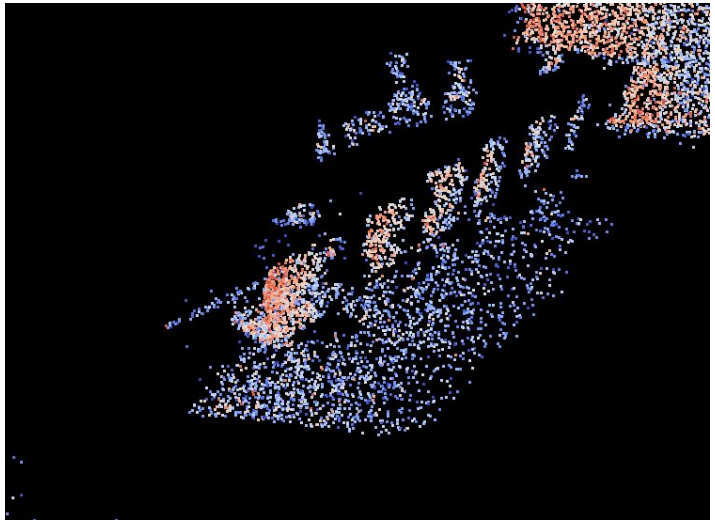
- High Probability and Spatial Density

$$NPD(p_i) = \frac{1}{L} * \sum_{p_j \in \mathcal{BQ}_{L,r}(p_i)} Pr(p_j)$$

NPD Score



NPD Filtering



Noise Removal

Neighbor Probability Density (NPD) Filtering

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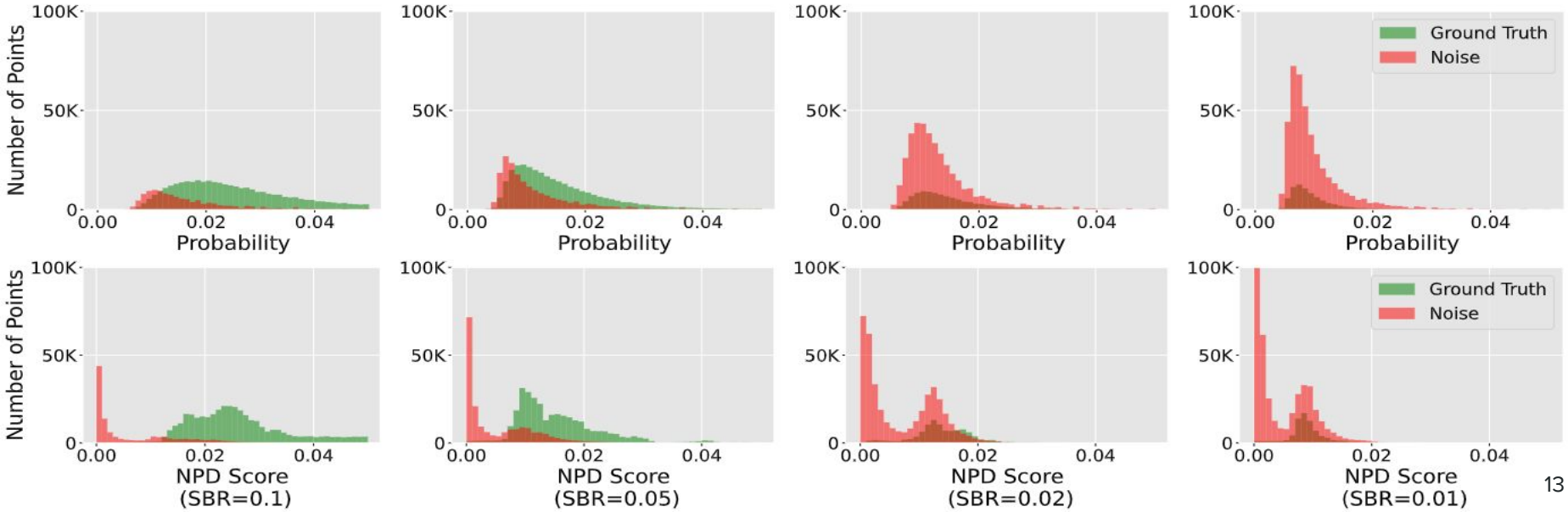
$$NPD(p_i) = \frac{1}{L} * \sum_{p_j \in \mathcal{BQ}_{L,r}(p_i)} Pr(p_j)$$

NPD Score

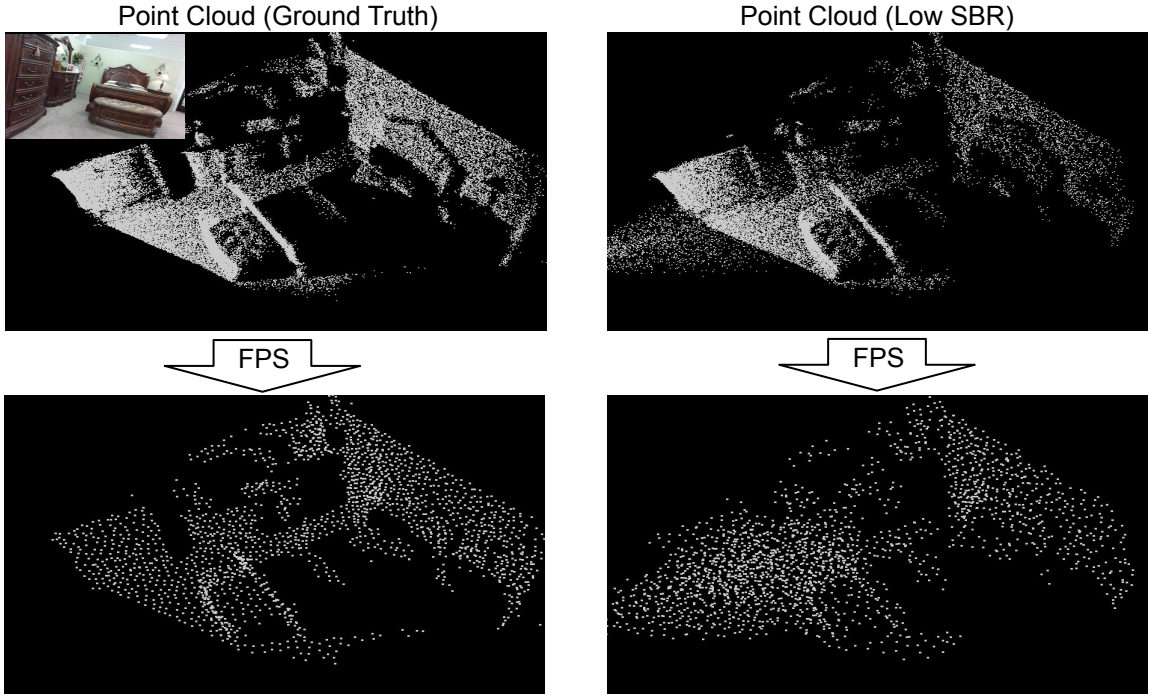


3D Inference with PPC

- Neighbor Probability Density Filtering (NPD)
- Farthest Probable Point Sampling (FPPS)
- Probability Aware 3D inference networks

Point Sampling under Low SBR

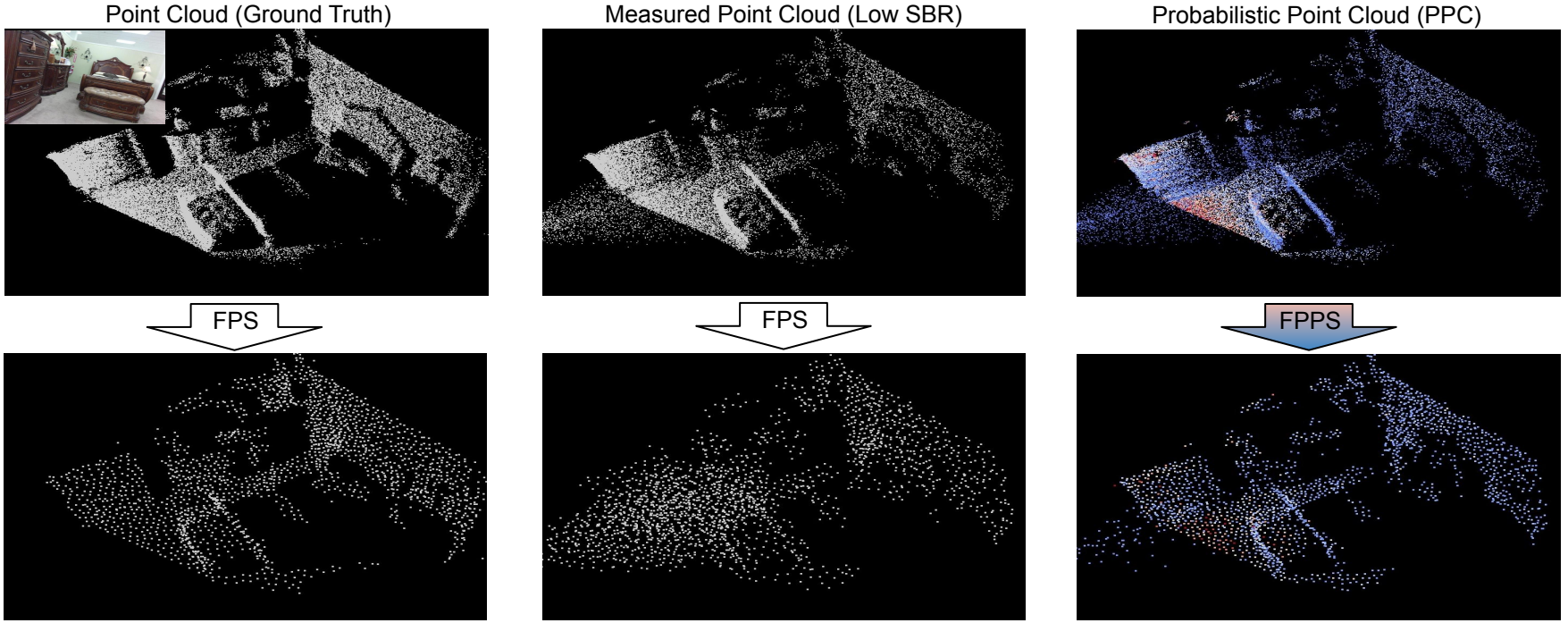
Farthest Point Sampling (FPS)



FPS prioritizes farther points, samples more noise

Farthest Probable Point Sampling (FPPS)

High probability candidate set for FPS



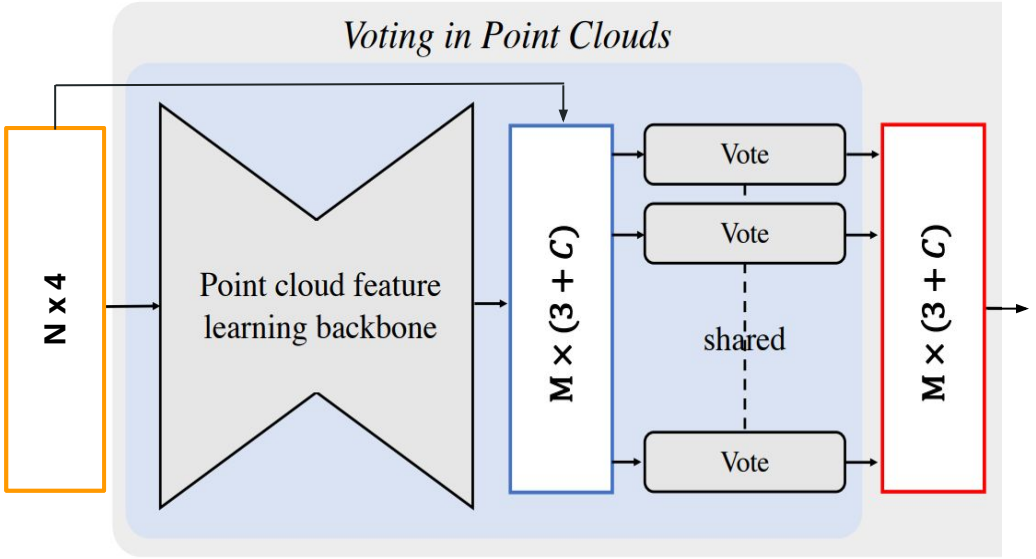
FPPS samples less noise

3D Inference with PPC

- Neighbor Probability Density Filtering (NPD)
- Farthest Probable Point Sampling (FPPS)
- Probability Aware 3D inference networks

Probability Aware 3D Inference

- Probability as point attribute
- Probability weighted feature vectors



Votenet 3D Object Detection Network

3D Object Detection Results

- LiDAR Setup and Real Captures

- Simulated Captures

3D Object Detection Results

- LiDAR Setup and Real Captures

- Simulated Captures

LiDAR Setup

ADAPS LiDAR

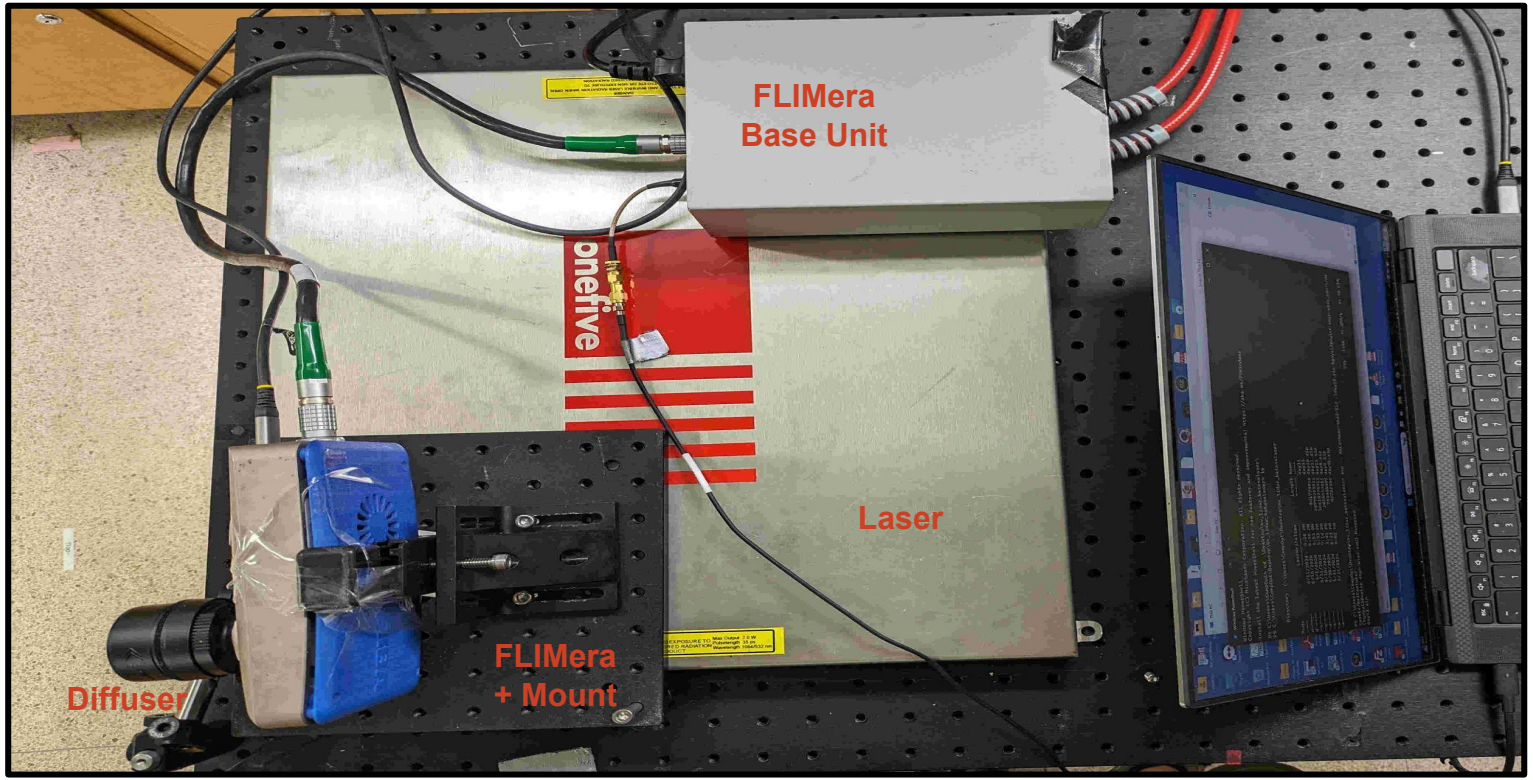
Chip Parameter	Spec
SPAD array	768 x 576
Macro pixel	3x3 SPAD binning
Macro pixel number	256 x 192
SPAD pitch	10um
SPAD Deadtime	~10ns
PDE (940nm)	>15%
Power Supply	VOP: -20V~30V AVCC: 3.3V DVCC: 1.1V IOVCC: 1.8V

Chip Parameter	Spec
Output mode	1) Grayscale mode 2) Histogram mode 3) Echo mode 4) Ranging mode
Interface	MIPI CSI-2 DPHY(4 Lane) I2C/SPI
Max detection range	200 m
Chip size	< 100 mm2
Power consumption	~ 3W
TX channel	4
Package	iBGA/COB

System Parameter	Spec
Detection Range	30m
FOV (H)	120°
FOV (V)	90°
Angular resolution	0.5° x 0.5°

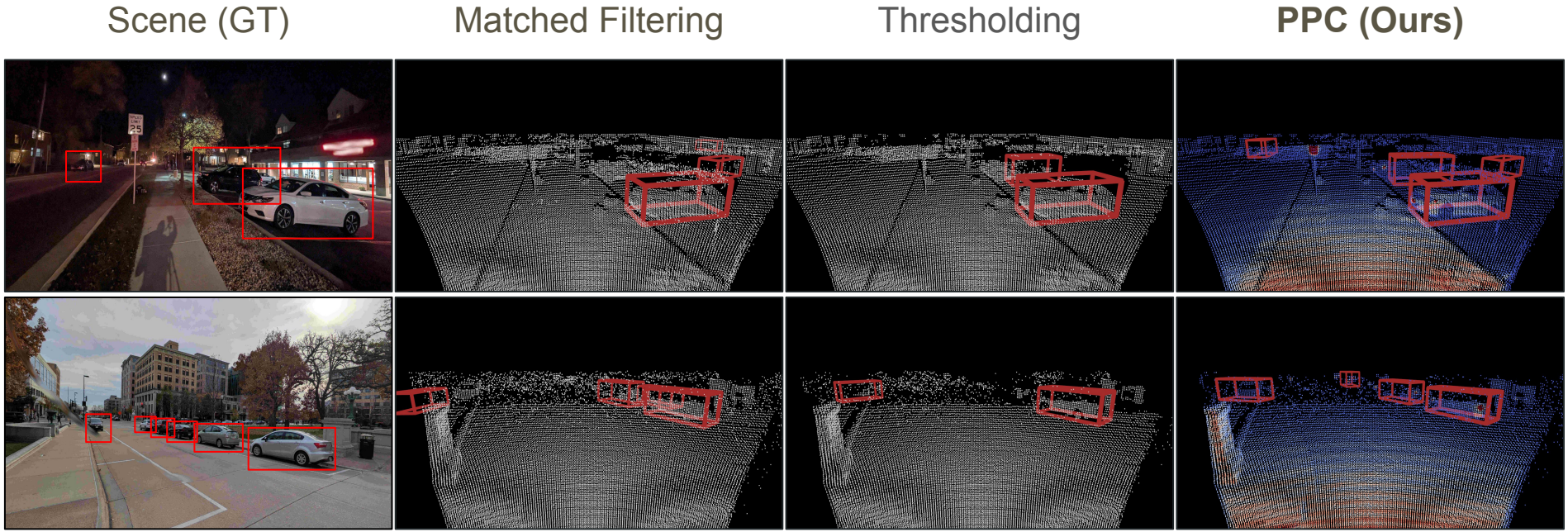
System Parameter	Spec
Frame rate	20 Hz
Accuracy	3cm
Laser wavelength	940nm
Eye safety	Class 1

LiDAR Setup



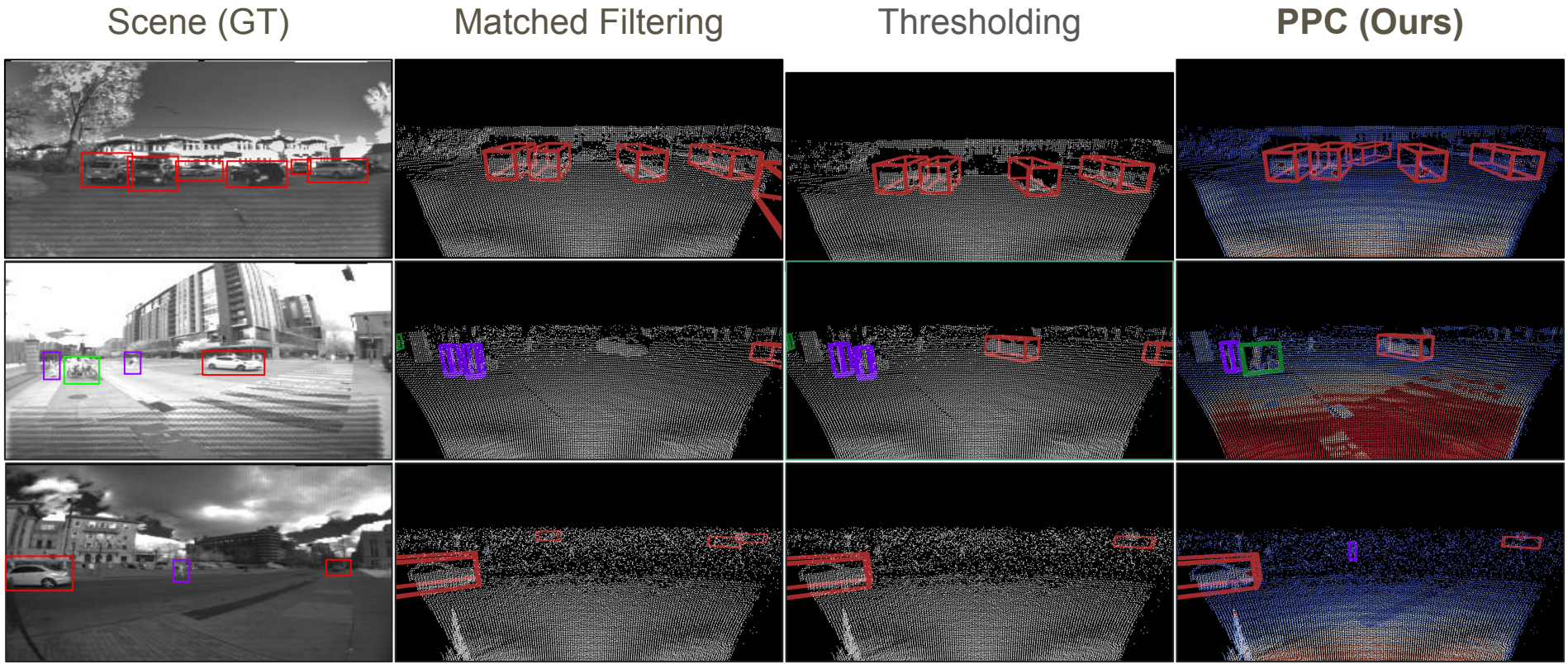
FLIMera LiDAR

3D Object Detection on Real Outdoor Captures



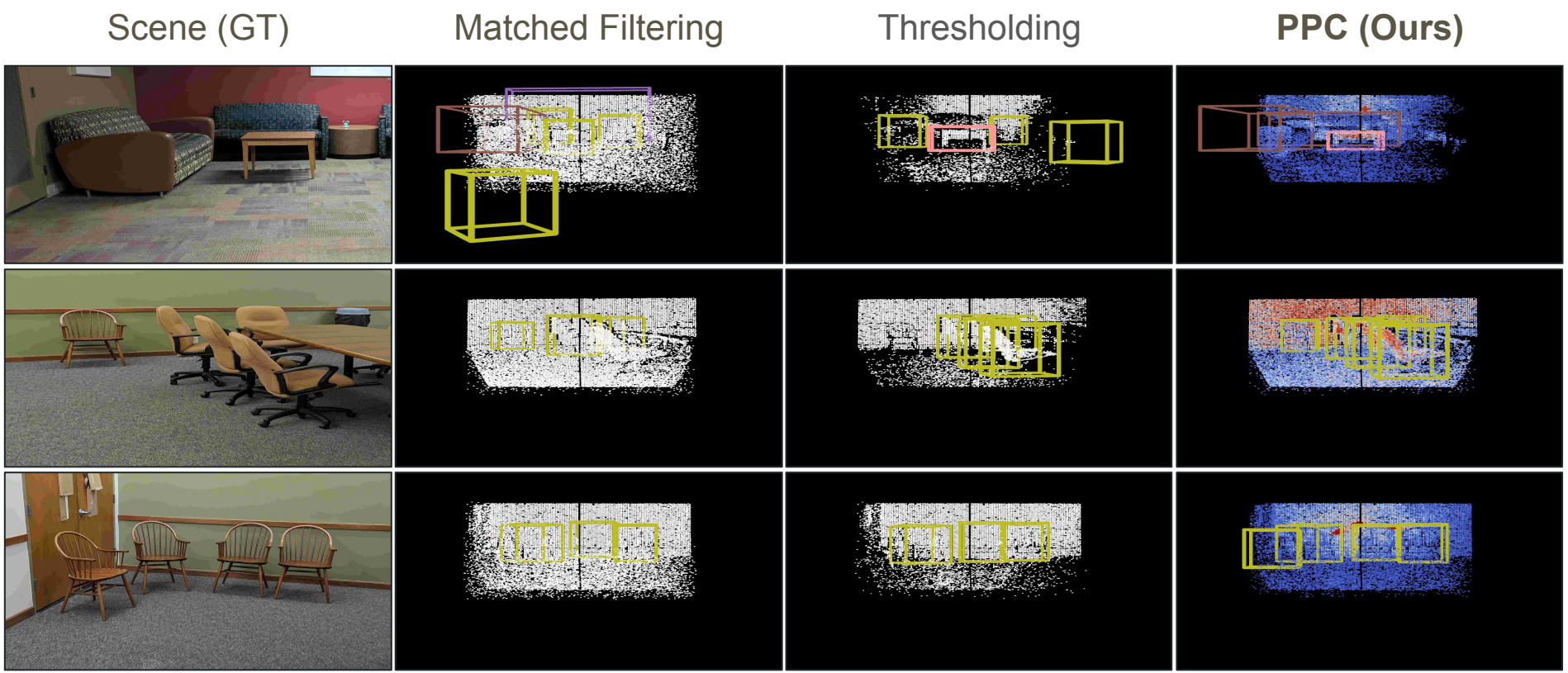
PPC detects all objects: farther cars

3D Object Detection on Real Outdoor Captures



PPC detects all objects: far car, pedestrian and bike

3D Object Detection on Real Indoor Captures



PPC detects all objects: couch, far chair and table

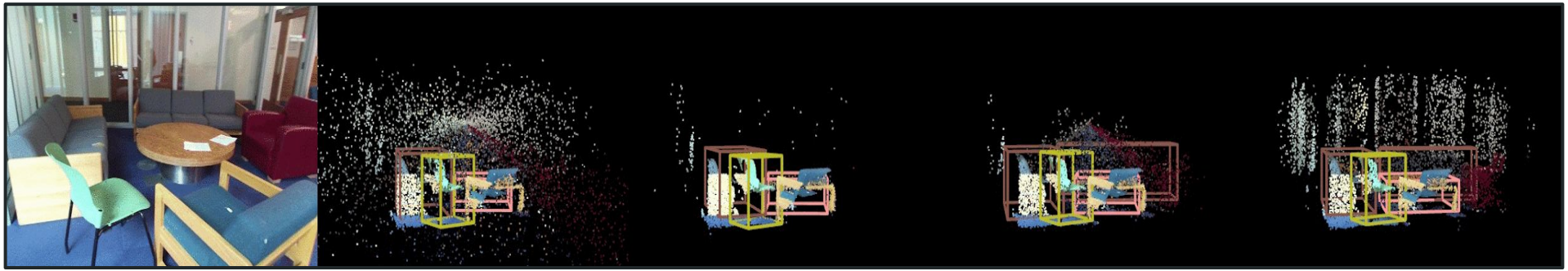
3D Object Detection Results

- LiDAR Setup and Real Captures

- Simulated Captures

3D Detection on SUN RGB-D

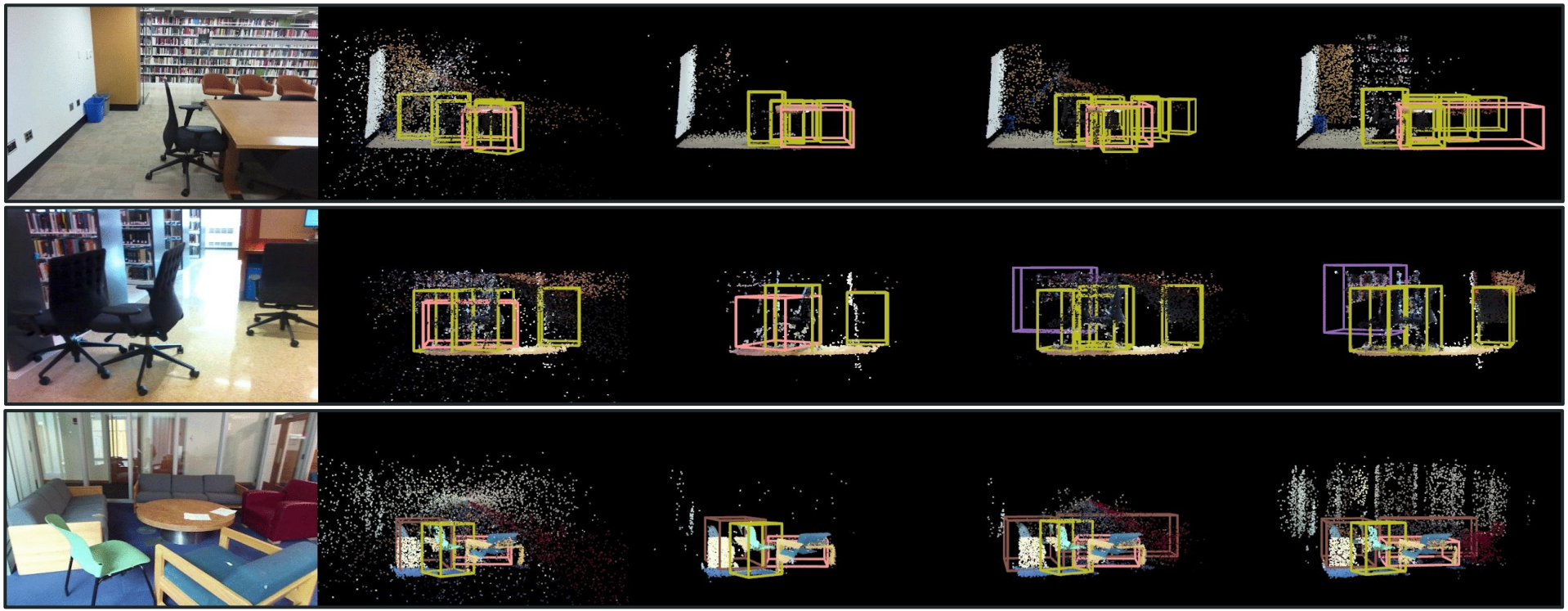
Scene | Matched Filtering | Thresholding | **PPC (Ours)** | GT



Avg. SBR	Clean		0.1		0.05		0.02		0.01	
	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50
Matched Filtering	51.34	27.45	42.43	20.49	38.77	17.57	16.95	5.05	11.34	2.73
Thresholding	57.11	33.21	51.27	28.62	46.44	24.86	29.58	14.81	16.47	6.45
PointClean Net [47]	54.58	31.89	45.65	26.44	40.19	19.15	18.24	8.05	12.78	3.01
Score Denoising [33]	57.38	34.02	53.19	29.45	48.61	25.78	26.35	13.73	14.55	4.73
PathNet [57]	57.16	33.87	52.16	28.79	47.11	24.89	25.45	12.96	13.87	4.56
PPC (Ours)	**58.61**	**34.99**	**54.29**	**31.15**	**52.46**	**30.20**	**38.49**	**16.47**	**29.42**	**13.16**

PPC outperforms all baselines significantly under very low SBR

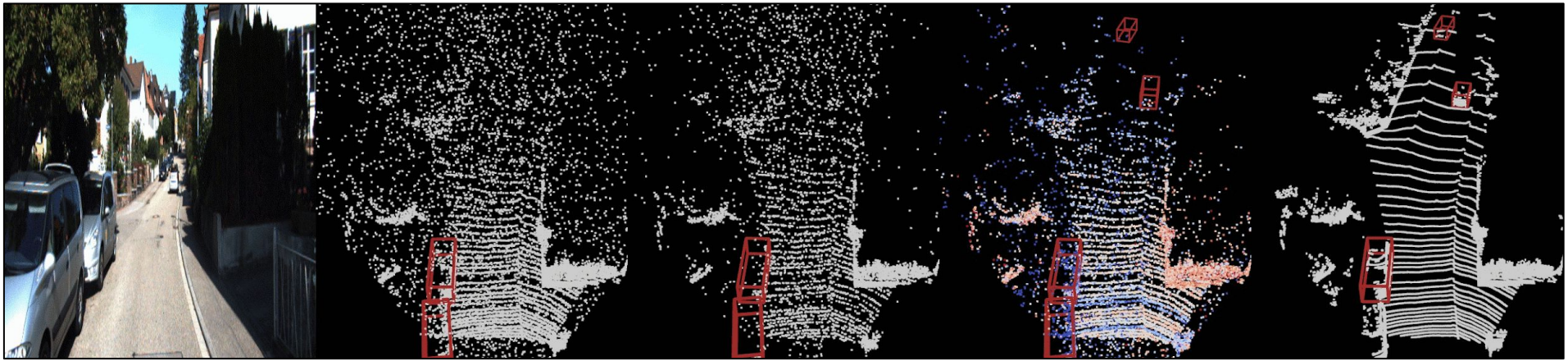
3D Object Detection on SUN RGB-D



PPC can detect farther objects: bookshelf, couch and chair

3D Detection on KITTI

Scene | Matched Filtering | Thresholding | **PPC (Ours)** | GT

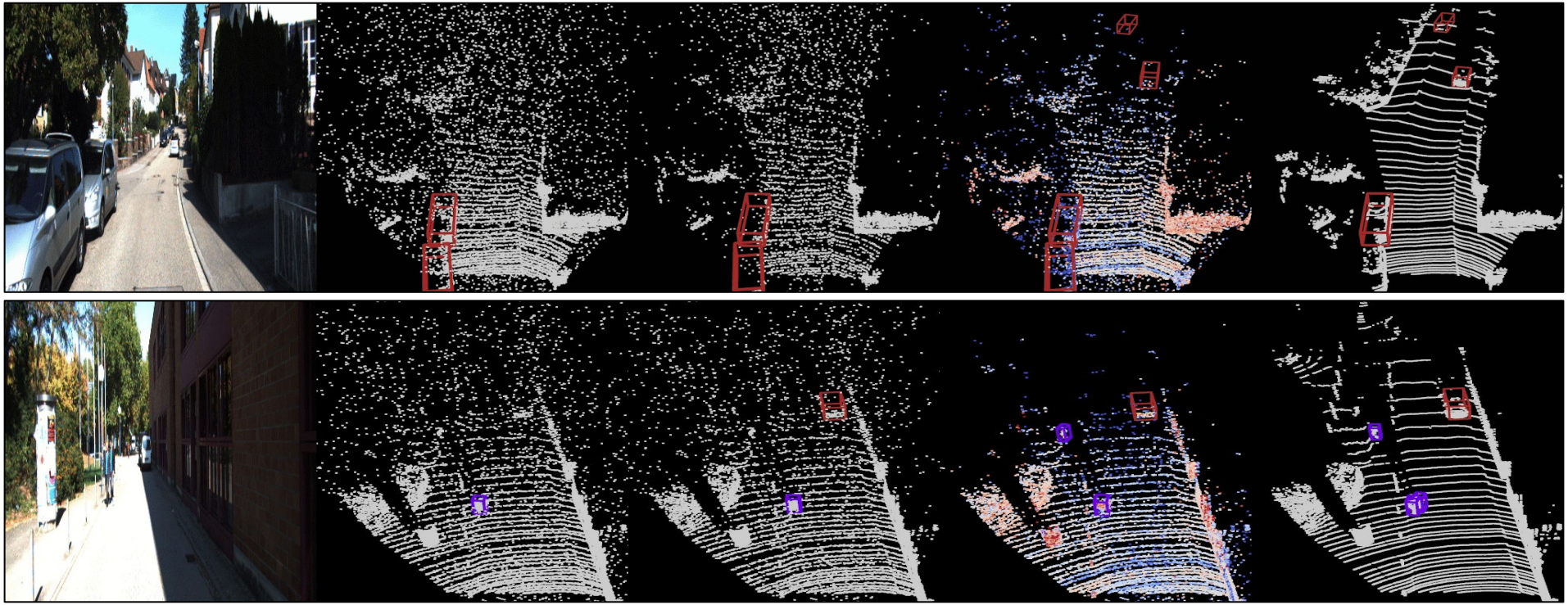


Avg. SBR	Clean			0.05			0.02			0.01			0.005		
	Car	Ped	Cyc	Car	Ped	Cyc	Car	Ped	Cyc	Car	Ped	Cyc	Car	Ped	Cyc
Matched Filtering	82.48	60.11	71.36	**73.14**	55.76	61.84	68.17	50.03	52.85	59.95	47.06	43.74	50.68	37.01	35.01
Thresholding	82.81	58.63	71.55	72.80	57.72	60.44	68.05	54.80	52.71	59.40	49.23	44.96	50.35	38.62	35.74
PPC (Ours)	**83.56**	**60.62**	**73.35**	73.03	**59.12**	**64.14**	**68.42**	**59.04**	**53.18**	**60.29**	**55.39**	**47.76**	**51.30**	**49.51**	**36.44**

PPC outperforms all baselines significantly under very low SBR

3D Object Detection on KITTI

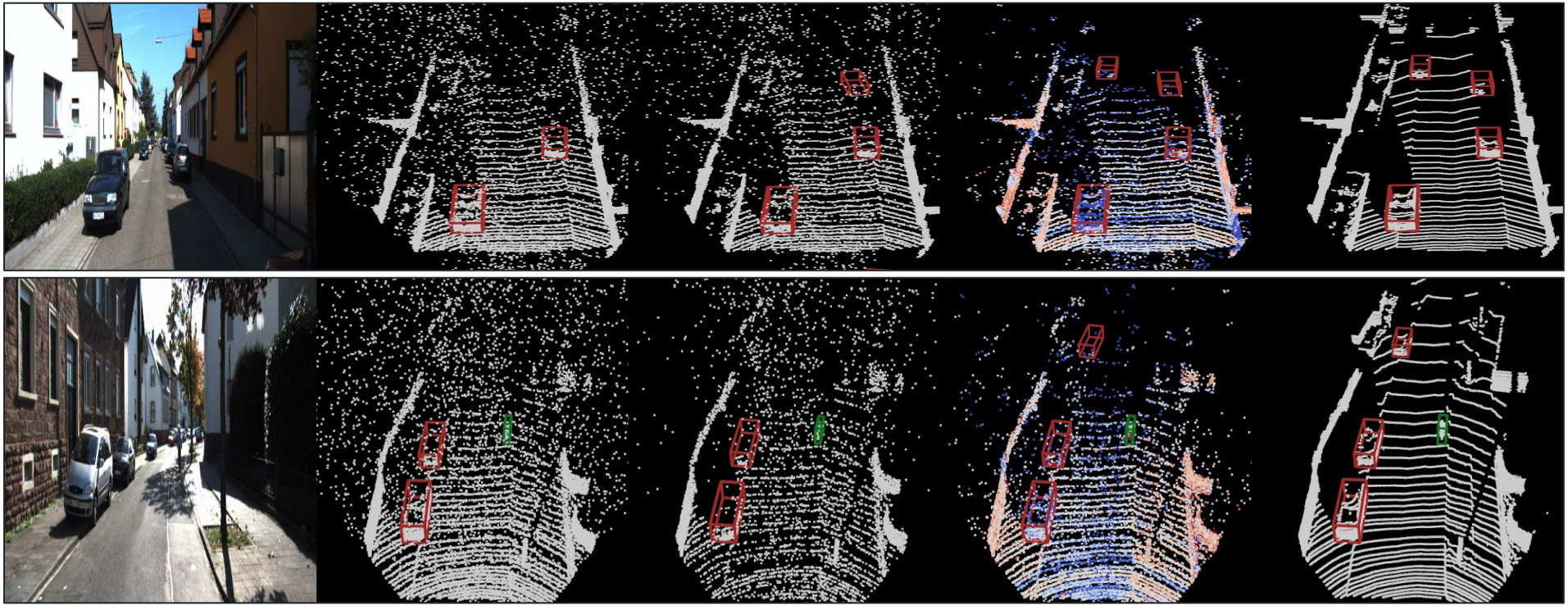
Scene | Matched Filtering | Thresholding | **PPC (Ours)** | GT



PPC can detect farther objects: car and far pedestrian

3D Object Detection on KITTI

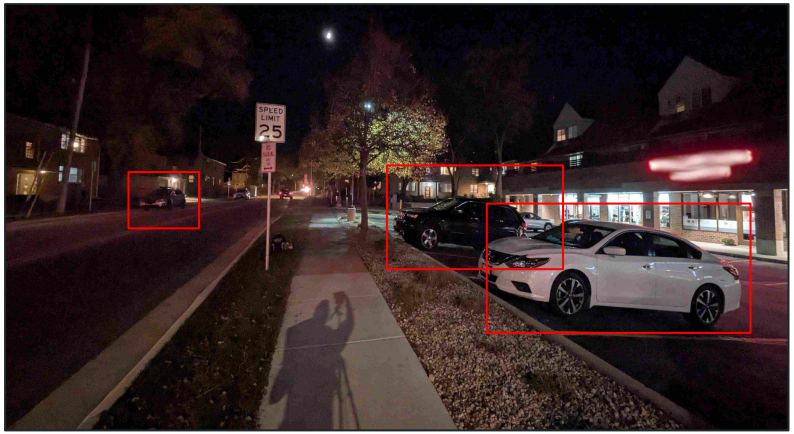
Scene | Matched Filtering | Thresholding | **PPC (Ours)** | GT



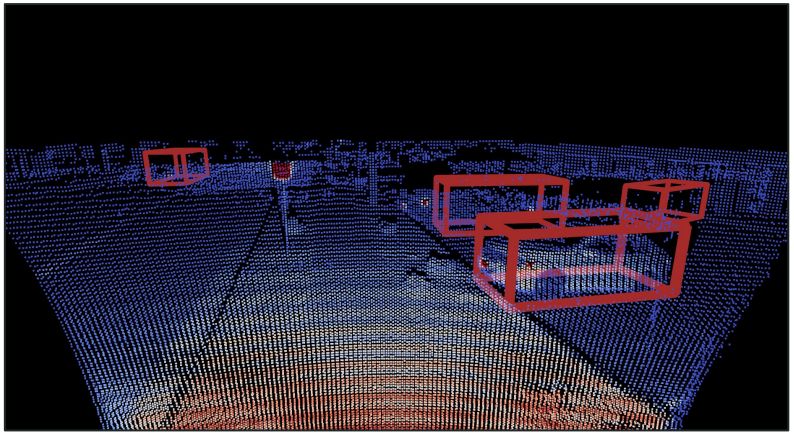
PPC can detect distant objects: cars

Summary

Scene



Probabilistic Point Cloud



Sensing: Confidence information from 3D sensors

Inference: Robust 3D perception using probabilistic point clouds

Thank You

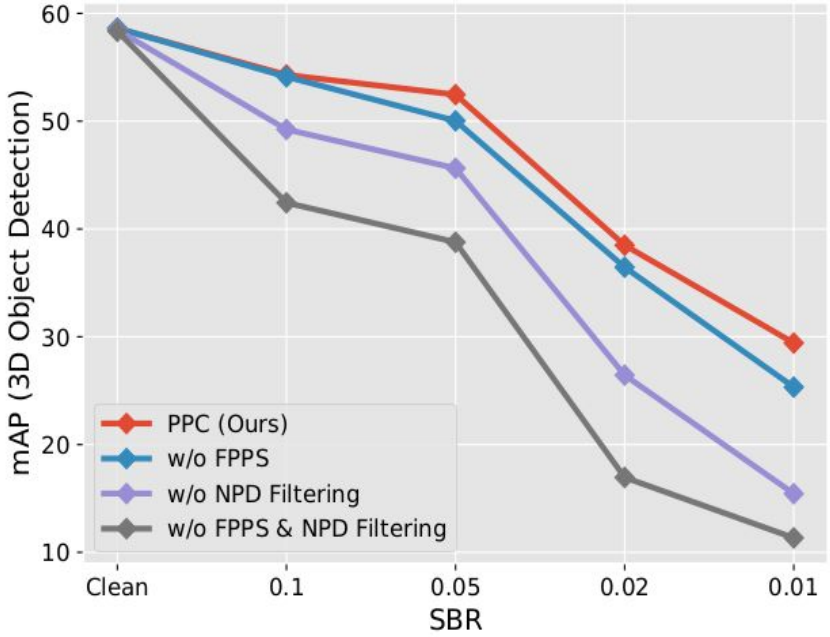
Questions?

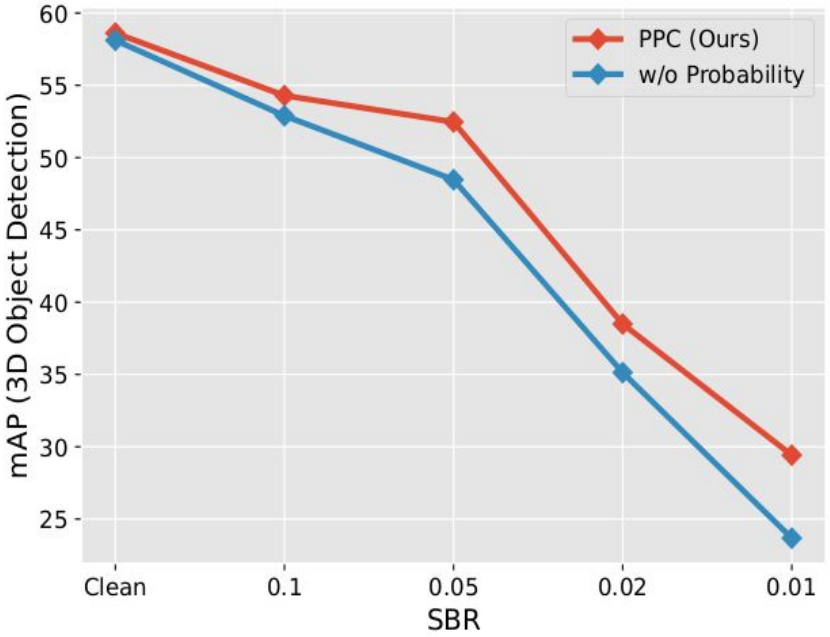
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Additional Results

Ablation Study

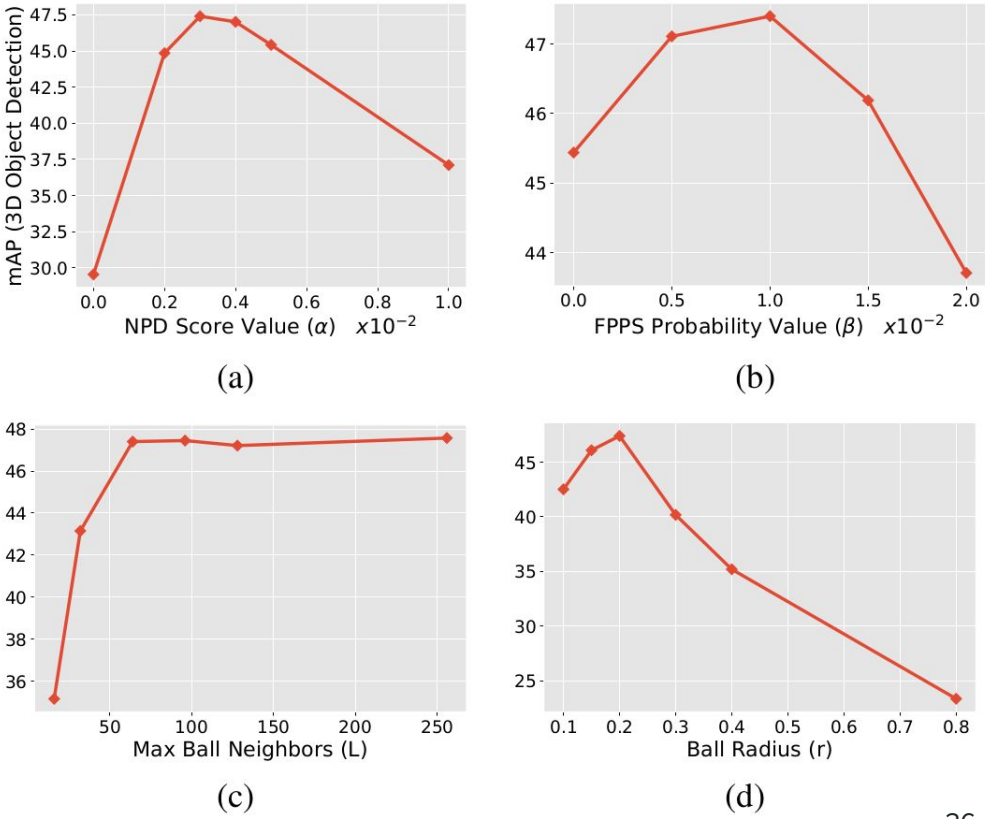
- Probability Attribute
- NPD Filtering and FPPS





Ablation Study

- NPD Score Hyperparameters
  - NPD Score (α)
  - FPPS Probability (β)
  - Max Ball Neighbors (L)
  - Ball Radius (r)



Camera-LiDAR fusion with ImVoteNet

Avg. SBR	Clean		0.1		0.05		0.02		0.01	
	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50
Matched Filtering	63.37	35.51	53.89	27.64	53.23	24.67	37.54	10.99	33.17	7.98
Thresholding	64.25	36.17	59.57	33.44	58.82	32.45	42.43	18.17	39.51	12.61
PPC (Ours)	**64.36**	**36.94**	**61.51**	**35.69**	**60.19**	**31.38**	**53.21**	**25.37**	**46.84**	**20.14**

PPC outperforms all baselines significantly on SUN RGB-D under very low SBR

PointPillars Detector

Avg. SBR	Clean			0.05			0.02			0.01			0.005		
	Car	Ped	Cyc	Car	Ped	Cyc	Car	Ped	Cyc	Car	Ped	Cyc	Car	Ped	Cyc
Matched Filtering	77.08	**52.78**	64.49	68.25	49.52	58.96	64.13	47.67	46.45	54.43	41.61	41.76	45.03	32.46	31.06
Thresholding	**77.34**	52.09	64.81	68.06	49.63	59.09	63.87	47.92	46.96	54.18	40.88	42.18	45.11	32.79	31.89
PPC (Ours)	77.19	52.12	**65.21**	**69.12**	**50.23**	**62.44**	**65.63**	**49.27**	**48.09**	**56.39**	**45.77**	**44.46**	**47.24**	**38.74**	**34.89**

PPC outperforms all baselines significantly on KITTI under very low SBR

Uni3DETR (Transformer-based) Detector

Avg. SBR	Clean		0.1		0.05		0.02		0.01	
	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50	AP@25	AP@50
Matched Filter	64.98	48.28	61.52	45.09	60.82	43.92	51.12	34.09	45.29	27.97
Thresholding	64.50	47.94	61.08	44.71	61.19	44.29	51.97	34.87	48.13	28.64
PPC (Ours)	**65.53**	**49.35**	**62.58**	**46.71**	**61.98**	**48.28**	**56.46**	**38.03**	**51.21**	**31.16**

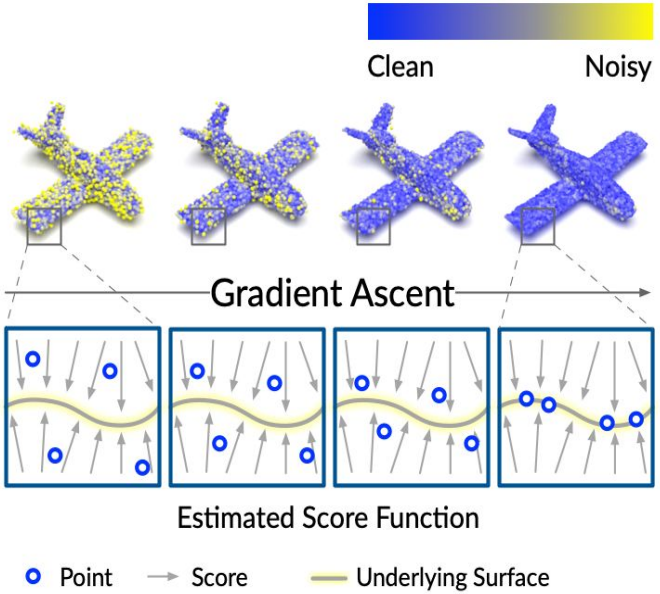
PPC outperforms all baselines significantly on SUN RGB-D under very low SBR

Category-wise Results on SUN RGB-D

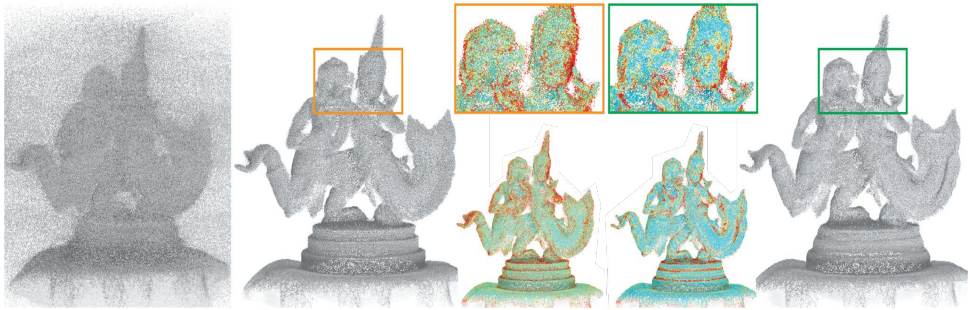
Category	Matched Filtering	Thresholding	PointClean Net [41]	Score Denoise [28]	**PPC (Ours)**
Bed	54.37	67.33	53.59	68.57	**72.97**
Sofa	16.20	28.15	22.00	38.25	**45.19**
Table	29.61	37.99	30.20	33.93	**40.47**
Bathtub	6.04	25.14	2.71	14.04	**54.32**
Desk	7.97	14.16	7.78	8.33	**17.37**
Bookshelf	2.12	4.85	0.67	1.01	**9.80**
Chair	22.05	34.27	22.92	27.45	**47.47**
Night Stand	3.10	14.45	7.41	10.23	**30.49**
Dresser	2.58	4.64	2.80	2.44	**13.73**

PPC is very effective on small categories under very low SBR

Denoising Networks



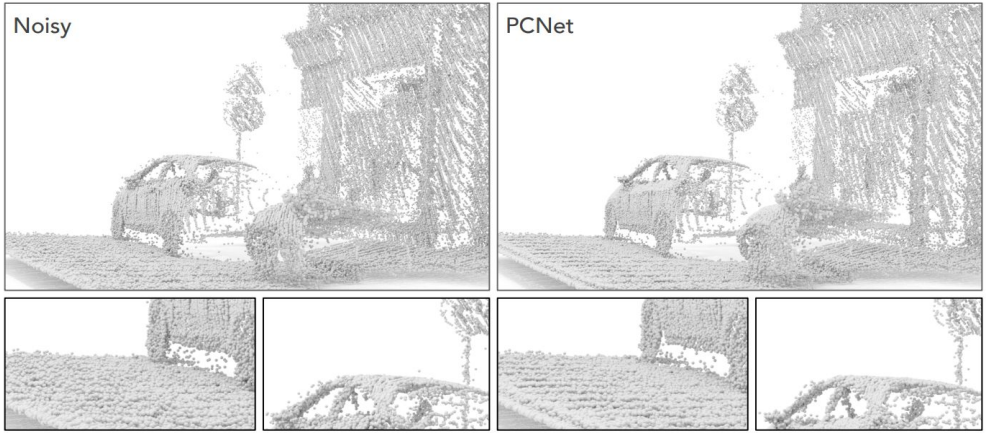
Score-based Denoising



PointClean Net

Should we use denoising networks for inference?

- Improves Surface Reconstruction
  - Not 3D Object Detection
- Local Isotropic Gaussian Noise
- Spurious point have no depth information



- Computational Overhead

	Matched Filtering	Thresh-olding	PointClean Net	Score-Denoising	PathNet	PPC (Ours)
Runtime (ms)	87	89	755	1345	867	95

Runtime

	Matched Filtering	Thresh-olding	PointClean Net	Score-Denoising	PathNet	PPC (Ours)
Runtime (ms)	87	89	755	1345	867	95

Comparison of inference time

3D Detection Results with PPC Variants

PPC-aware detection models show better performance

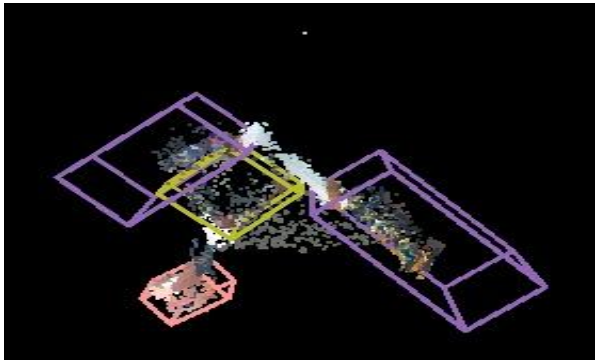
Avg. SBR	Clean	0.1	0.05	0.02	0.01
Thresholding	57.11	51.27	46.44	29.58	16.47
PPC	58.61	54.29	52.46	38.49	29.42
PPC w/ prob point att	58.35	55.73	53.67	39.10	30.58
PPC w/ wt. point feat vec	59.29	55.86	52.95	37.68	30.42
PPC w/ wt. obj score	58.53	55.18	53.15	38.76	30.17
PPC w/ all	**59.35**	**56.11**	**53.45**	**39.87**	**30.81**

Table 5. AP@25 results on SUN RGB-D with PPC variants.

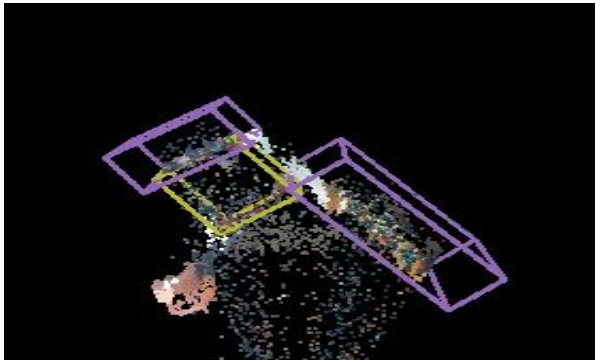
3D Detection Results

Scene

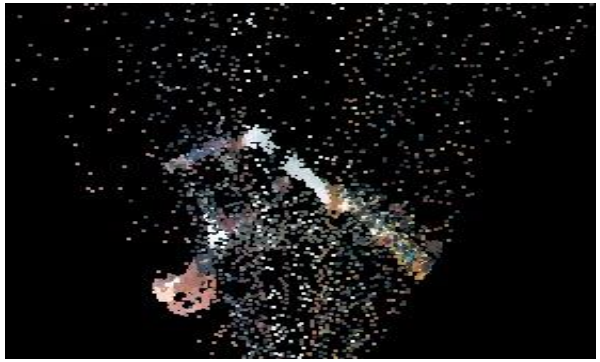
Ground Truth



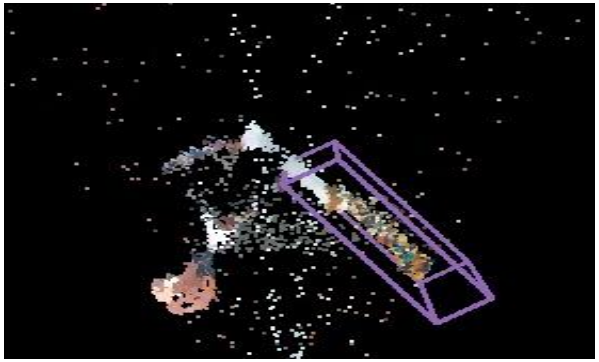
PPC (Ours)



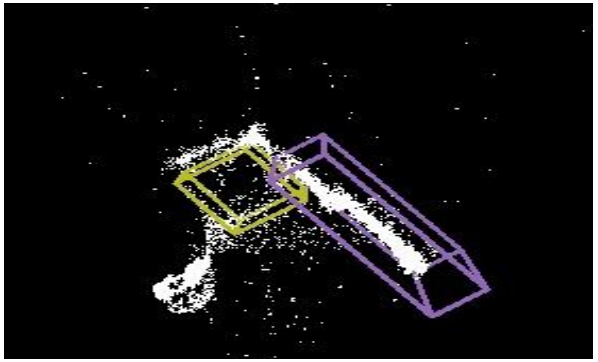
Matched Filtering



Matched Filtering + Threshold



Score-Denoising

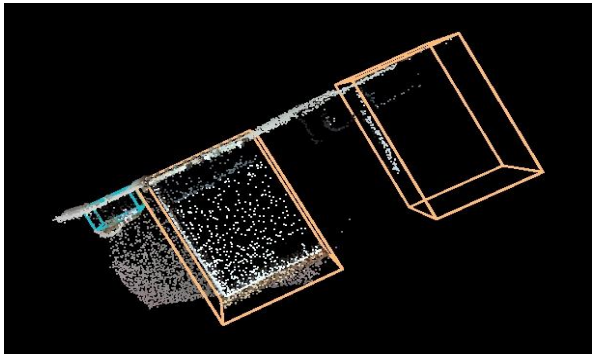


PPC can detect smaller and farther objects

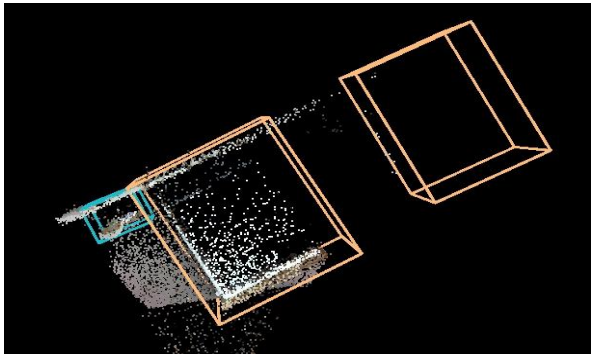
3D Detection Results

Scene

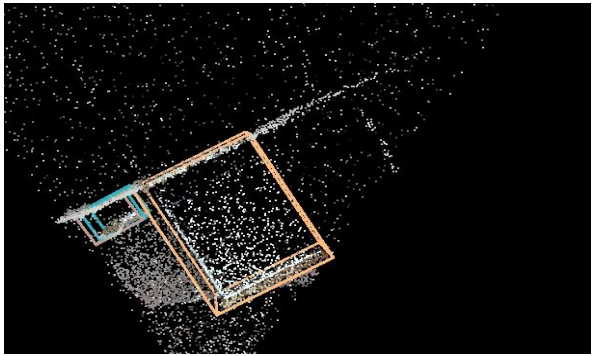
Ground Truth



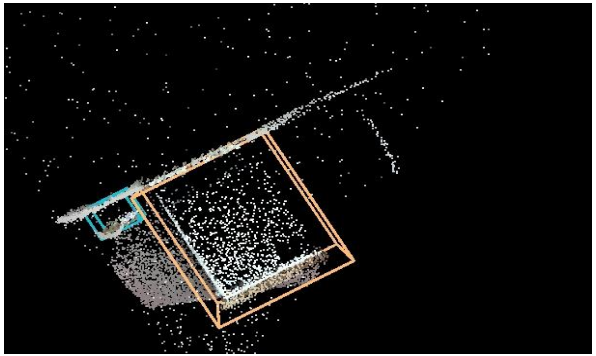
PPC (Ours)



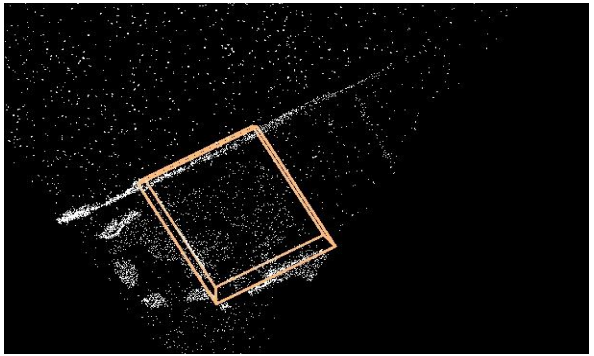
Matched Filtering



Matched Filtering + Threshold



Score-Denoising



PPC detects smaller and farther objects